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URBAN STORMWATER QUALITY, DEVON PILOT CATCHMENT, CITY OF STRATFORD

Prepared for the Task Force on
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by

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URBAN STORMWATER QUALITY, DEVON PILOT CATCHMENT, CITY OF STRATFORD

Z. Novak[1], B.A. Whitehead[1]

SYNOPSIS

Data on precipitation, stormwater runoff and runoff quality were collected for a wide range of hydrologic events from a typical urban catchment - Devon, in the City of Stratford. The data were analysed to define precipitation/runoff/pollutant inter-relationships in order to characterize the typical runoff pollutant loadings on an event and seasonal basis.

The event pollutant loading increases with increasing runoff volume while the average event concentration decreases with increasing runoff volume. Smaller runoff events however, occur more frequently and as a result, contribute the major portion of the total seasonal pollutant loadings. Higher pollutant concentrations were found at the early stages of the runoff event.

Relatively small water quality ponds can effectively reduce seasonal pollutant loadings to a receiving stream by natural settling. These ponds can capture small runoff events plus the first portions of larger runoff events.

KEYWORDS

Urban pilot catchment; stormwater runoff; stormwater quality; stormwater quality control by storage ; Stratford - Avon River Environmental Management Study.

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RÉSUMÉ

Dans un bassin versant urbain type, à savoir Devon, dans la Ville de Stratford, on a recueilli des données sur les précipitations, les écoulements d'averse et la qualité des ruissellements en ce qui concerne une grande variété d'événements hydrologiques. Les données ont été analysées afin de déterminer la relation entre les précipitations, les ruissellements et les polluants de façon à pouvoir identifier les arrivées types de polluants provenant des ruissellements ponctuels et saisonniers.

L'arrivée ponctuelle de polluants augmente lorsque le volume du ruissellement s'accroît, tandis que la concentration ponctuelle moyenne diminue lorsque le volume du ruissellement augmente. Cependant, les petits ruissellements ponctuels sont plus fréquents et, par conséquent, sont responsables de la plus grande partie des arrivées saisonnières globales de polluants. On a décelé de plus fortes concentrations de polluants au stade initial du ruissellement ponctuel.

Des étangs de décantation relativement petits peuvent, grâce à la décantation naturelle qui s'y effectue, réduire efficacement les arrivées saisonnières de polluants dans les cours d'eau. En effet, ces étangs peuvent absorber les petits ruissellements ponctuels ainsi que les fractions initiales des ruissellements ponctuels plus importants.

INTRODUCTION

In 1975 the Thames River Basin Management Study concluded that during low flow periods, the Avon River has an extremely low assimilative capacity. Further detailed investigations by the Ministry of the Environment in 1977 and the resultant report in 1979 indicated that Provincial Water Quality Objectives were not being met for several parameters. The recommendations brought forward suggested that improved water quality levels could only be achieved as a result of combined efforts in the areas of improved urban and agricultural runoff controls and possibly by the use of instream methods.

The Stratford-Avon River Environmental Management Project (SAREMP), a two-year study, was initiated on April 1, 1980 in an effort to resolve Avon River water quality problems. Part of the study included an assessment of urban non-point sources of pollution from the City of Stratford.

The objectives of this phase of the Avon study were:

(1) to assess the quality and quantity of urban stormwater runoff under existing land use conditions; and,

(2) to identify and evaluate feasible control options required to reduce pollutant discharge in urban stormwater runoff under existing land use conditions.

A program of data collection was required to characterize runoff pollutant loadings from a wide range of hydrologic events. Three small pilot catchments were selected on the basis of land use criteria. Data on precipitation, runoff quantity and quality data were collected. The quality parameters analysed were suspended solids, oxygen demanding materials, nutrients, some trace metals and bacteria. The data were also used for the development of analytical techniques and a model covering the entire City of Stratford. The model was then applied to aid in completion of the above objectives (Whitehead and Novak, 1982).

One of the pilot catchments - Devon - provided very detailed and extensive results regarding the quality of urban stormwater runoff discharges. Presentation and evaluation of these results is the subject of this paper. The collected data were analysed on an event as well as seasonal basis. Emphasis was given to evaluation of relationships between the total runoff volumes and pollutant loadings of individual events and their seasonal frequencies. In addition, an investigation of stormwater quality control by storage was made.

DESCRIPTION OF THE STUDY AREA

General

The Avon River, located in Southwestern Ontario, is a tributary of the Thames River. The watershed, shown in Figure 1, has an area of one hundred and forty eight square kilometers, a length of about twenty kilometers, and a width varying between two and seven kilometers. The river flows through the centre of the watershed in an east to west direction.

The watershed land use is approximately 88 percent rural and 12 percent urban. The urban land use is concentrated in the City of Stratford.

City of Stratford

The City of Stratford has a developed area of 1357 hectares and a land use distribution of: 54 percent residential, 10 percent commerical, 2 percent institutional, 24 percent industrial, and 10 percent open. These land uses are drained by separate sanitary and storm sewer systems.

During wet weather, surface runoff resulting from excess precipitation initiates a washoff of pollutants accumulated on land use surfaces. The washoff of pollutants already includes the load proportion from polluted rainfall. Pollutant loads are transported by the storm drainage network and are discharged directly via numerous outfalls into the Avon River. Not all of the outfalls could be monitored from a practical point of view, therefore only three representative pilot catchments were selected for such a task.

Pilot Catchment

The location of the Devon pilot catchment is shown in Figure 2. This catchment has an area of 34.2 hectares and is 90 percent developed. The land use distribution consists of 43 percent residential, 41 percent commercial and 16 percent open space.

The Devon catchment was selected on the basis of the proportion of residential, commercial and open land uses. This distribution was also representative of the land use proportion of the entire city: high density (50%), low density (40%) and open land use (10%). Low density refers to single family residential areas while high density encompasses high density residential, commercial, institutional and light-medium industrial land uses. For this reason Devon was considered to be of key importance in characterizing urban runoff from the City of Stratford.

DATA COLLECTION AND SUMMARY

The data collection program extended over 1980 and 1981. Emphasis was placed on the period between May to September for which a

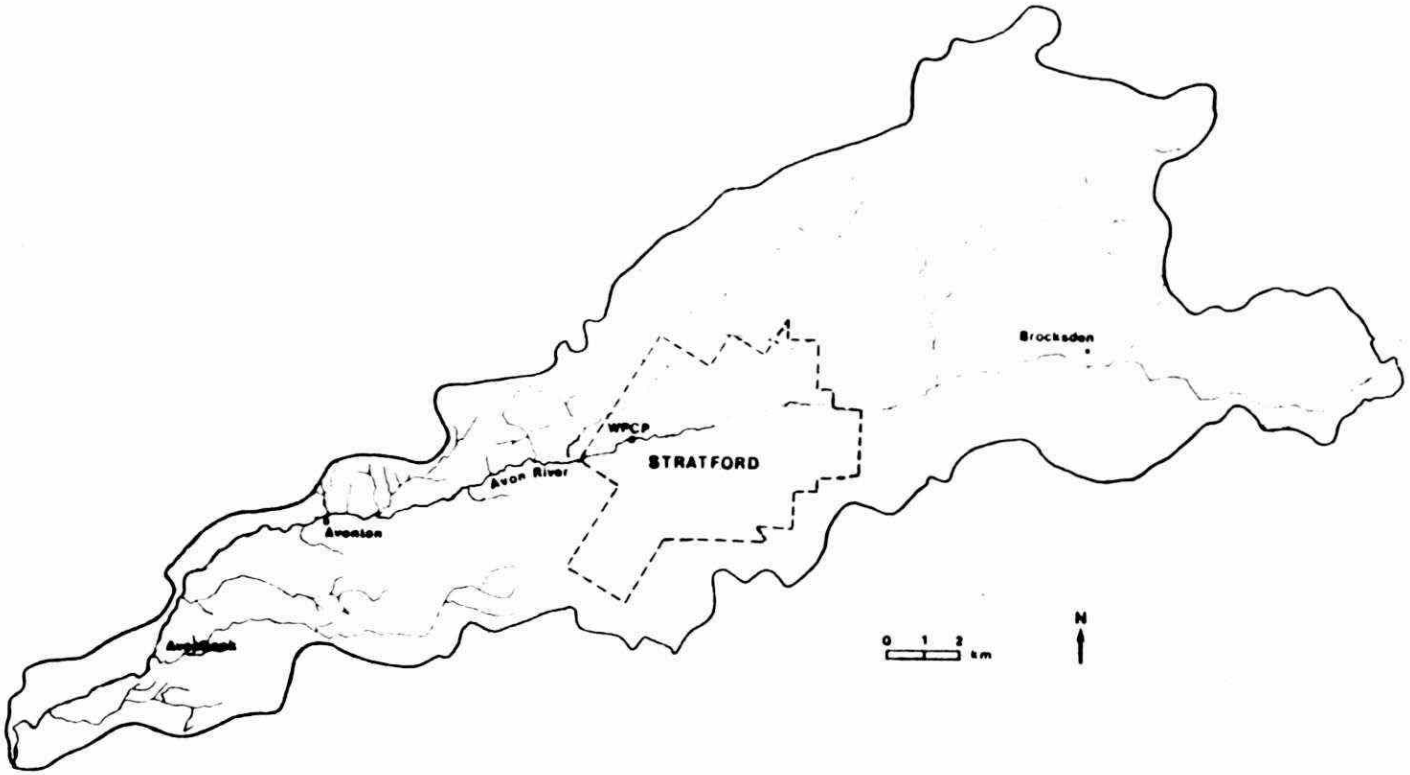

Figure 1. Avon River drainage basin.

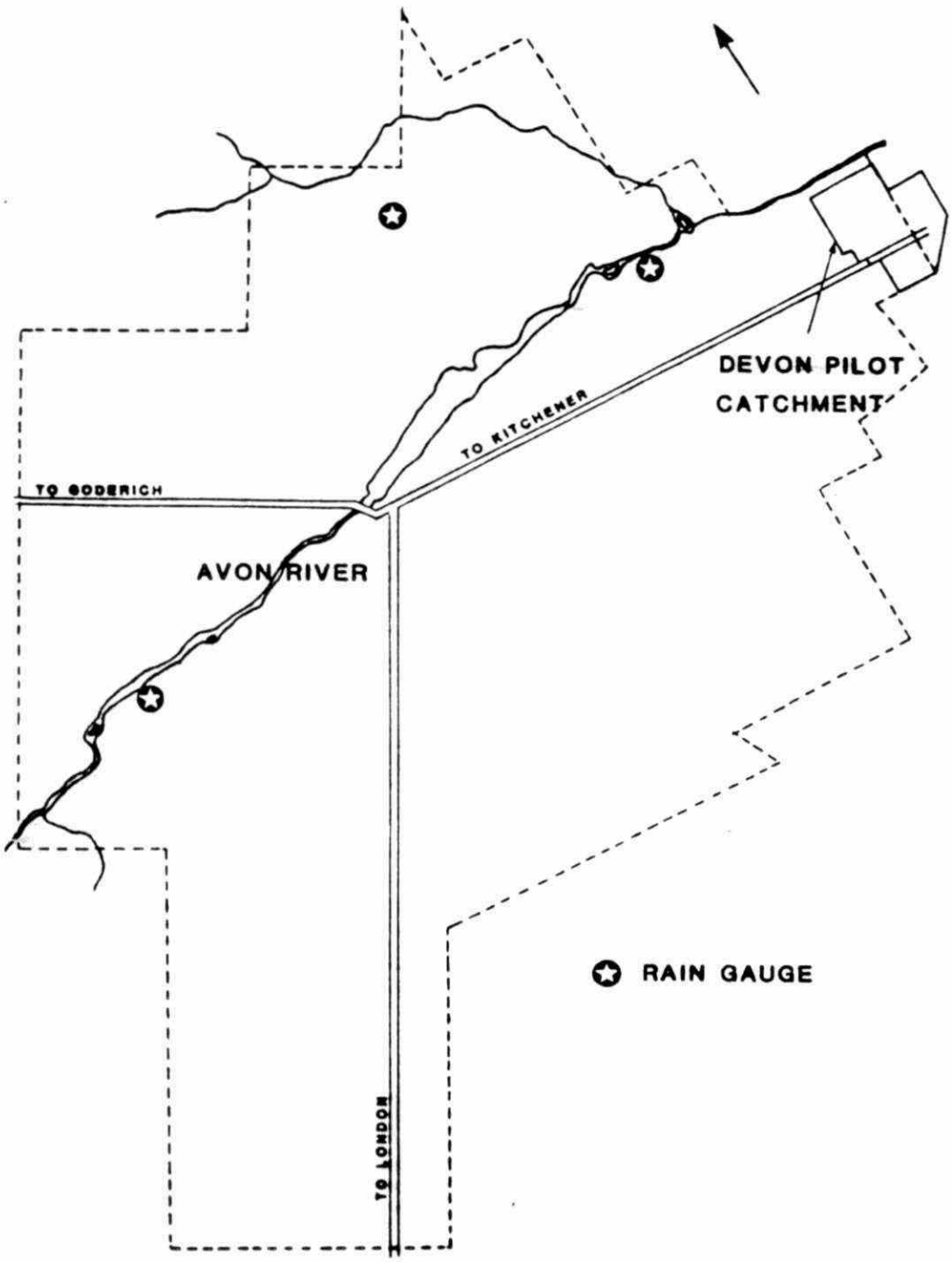

Figure 2. City of Stratford.

continuous precipitation record was obtained. In addition, runoff quantity and quality was measured for numerous storm events. Precipitation was monitored at three recording rain gauge stations spanning the city in triangular formation as shown in Figure 2. These gauges provided reliable records of preciptation occurring in the pilot catchment as well as a means of obtaining a composite record covering the whole city. The precipitation record at each station was based on a tipping bucket rain gauge to record precipitation intensity and a standard rain gauge to record total volumes. A summary of event statistics is presented in Table 1.

These statistics indicate that the average rainfall and average intensity was 6.0 mm and 1.23 mm/hr., respectively. Rainfall events occurred approximately every two days and lasted 7 hours on average. Between May and September of 1980 a total precipitation of approximately 330 mm fell on the City of Stratford. This value was an average amount of precipitation for the period of 1969 to 1981. In 1981 a higher rainfall of approximately 414 mm was recorded.

Table 1. Summary of 1980/81 rainfall events.

	Rainfall mm	Duration hours	Inter-Event Time hours	Average Intensity mm/hour
FIRE STATION				
Mean	5.6	8.2	43.3	1.01
Standard Deviation	11.3	14.6	55.7	1.17
Range	0.1-95.0	1.0-73.5	0.3-300.6	.05-8.0
Number of Events	130	130	130	130
WPCP				
Mean	6.5	5.2	47.2	1.55
Standard Deviation	10.2	5.7	71.7	2.19
Range	0.2-60.0	0.2-21.3	0.3-36.0	0.1-14.3
Number of Events	106	106	106	106
WORKS YARD (1980)				
Mean	4.1	2.9	35.7	1.25
Standard Deviation	7.1	2.7	46.7	1.84
Range	0.3-32.5	1.0-17.0	1.0-176.0	0.17-11.2
Number of Events	62	62	62	62
ONTARIO HYDRO (1981)				
Mean	8.8	14.5	62.2	1.08
Standard Deviation	13.4	18.4	66.7	1.01
Range	0.1-64.8	0.2-72	0-293.0	.06-4.92
Number of Events	47	47	47	47

Flow and water quality monitoring was conducted at the storm sewer outfall of the pilot catchment using automated equipment. A total of 42 runoff events were measured for Devon. The measurements cover most of the seasonal events excluding negligible runoff events (less than 0.1 mm) and some events lost due to recorder malfunction. The runoff volumes refer to direct surface runoff excluding dry weather flow. A summary of collected runoff events are presented in Table 2.

The summary indicated that runoff duration lasted approximately between 1 hour to 21 hours. The average was 6 hours. The peak flows for these events varied from 43 to 700 liters per second with the average peak flow being 200 liters per second. A good range of runoff depths or volumes from 0.6 millimeters up to 43 millimeters was observed. The overall average event runoff was 7.5 millimeters. Note that depth of precipitation and runoff over a catchment area automatically refers to volume.

Runoff quality samples were collected sequentially for a total of 20 storm events. A summary of the urban runoff quality data for Devon consisting of suspended solids (SS), 5-day biochemical oxygen demand (BOD_5), total nitrogen (TN) and total phosphorus (TP) is presented in Table 3. The pollutant concentrations ranged between 45-532 mg/l SS, 4.5-31.4 mg/l BOD_5, 1.9-9.3 mg/l TN and 0.13-0.91 mg/l TP.

Table 2. Summary of 1980/81 urban runoff events.

	Duration hrs.	Peak Flow l/sec	Runoff Volume m^3	Runoff Volume mm
1980*				
DEVON				
Mean	11.0	187	1421	3.8
Standard Deviation	5.9	201	1298	3.6
Range	4.4-21.3	71-779	233-4508	0.6-12.6
Number of Events	11	11	11	11
1981**				
DEVON				
Mean	4.2	203	726	8.8
Standard Deviation	3.8	163	776	9.4
Range	1.1-13.0	43-742	56-3269	1.0-42.9
Number of Events	31	31	31	31

*Runoff volumes include baseflow contributions.
**Runoff volumes exclude baseflow contributions.

Table 3. Summary of urban runoff quality data.

	SS	BOD_5	TN	TP
Devon 1980/81				
Mean mg/l	190	13.7	4.7	0.48
Standard Deviation mg/l	123	8.4	2.2	0.21
Range mg/l	45-532	4.5-31.4	1.9-9.3	0.13-0.91
Number of Samples	20	20	20	20
Adopted Values for Ontario				
Mean mg/l	170	14.0	3.5	0.35

The quality of Devon stormwater runoff is comparable to the adopted values for Ontario runoff composition (Waller and Novak, 1978). A comparison of average conventional parameter concentrations is shown in Table 3.

A sample storm event, observed on the Devon catchment, was plotted in Figure 3 to demonstrate the relationship between rainfall, runoff and pollutant washoff. The storm was generated by a 9 millimeter rainfall that resulted in a 2.6 millimeter runoff. The runoff responded rapidly to direct changes in the precipitation rate with very little lag time even at the beginning of the event. This is attributed to a large total impervious area, found to be 37 percent, and an efficient drainage system. In addition, it was estimated that the depression storage of impervious surfaces is on the order of 1.5 mm, common to many urban catchments. The shape of the pollutographs indicated that SS, BOD_5, TN and TP were subject to a first flush washoff. The pollutants exhibited significantly higher concentrations in the initial stages of runoff.

DATA EVALUATION AND INTERPRETATION

The collected precipitation, runoff and quality data were analysed to define their inter-relationships. The objectives of this evaluation were to characterize the typical pollutant loadings for a range of events and to determine the load distribution in a given season.

The analysis was carried out in several sequential steps. First, the relationship between precipitation and runoff was studied to enable the prediction of a runoff volume for a given precipitation event and urban land use. This led to an investigation of the seasonal occurrence of the event runoff magnitudes in order to see which events may be more significant due to their frequent occurrence. The averaged event runoff volume magnitudes and

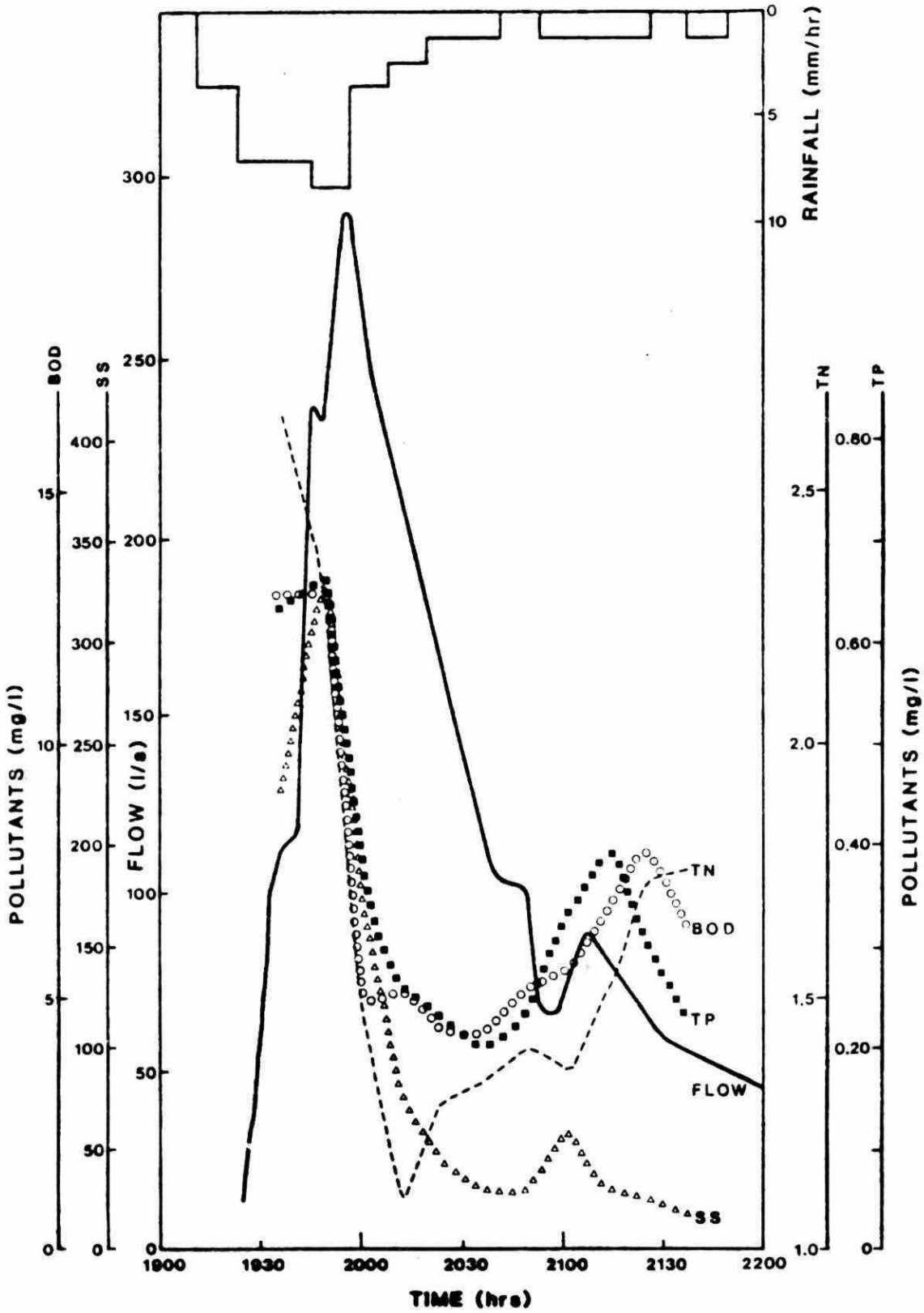

Figure 3. Example storm event.

occurrences were later superimposed on event water qualities. The event water quality analysis consisted of a study of the relationships between event runoff and associated pollutant loads. The final resulting product function between event runoff, pollutant load and occurrence explains which range of event runoff magnitudes contribute most to seasonable pollutant loads. Detailed discussions of the data evaluation and interpretation are given below.

The relationship between precipitation and runoff was developed for the pilot catchment. The depth of precipitation versus the depth of runoff was plotted as shown in Figure 4. The slope of the resulting curve provided an average estimate of the fraction of rainfall which appeared as immediate runoff. This fraction of 0.24, remained constant for the range of collected events. This was expected as a result of the observed impervious areas which contribute to major portions of surface runoff.

A preliminary investigation of storm event occurrence was conducted using Devon catchment data for the 1981 season. The frequency of seasonal event occurrence were plotted against runoff depth as shown in Figure 5. This relationship clearly demonstrates that small storm runoff events up to 4.0 mm occur frequently. In the case of Figure 5, approximately 85 percent of the events were less than 4 mm. A runoff of 4 mm was generated by a rainfall of approximately 16 mm. The data indicates that events of this magnitude or greater, may occur less frequently than once a month. This 1981 seasonal precipitation distribution was compared to an average nine year record from the period between 1969 to 1980. Both distributions were similar with slight deviation in the magnitude of the 1981 curve. This confirms that the 1981 accumulative precipitation was just above average.

The relationship between total event pollutant load and event runoff volume was developed. Suspended solids, biochemical oxygen demand, total nitrogen and total phosphorus loadings per unit area were plotted against corresponding depths of runoff for the 1981 Devon data as shown in Figure 6. The trend and scatter of the data suggested a definite relationship between event pollutant load and runoff volume. Therefore, the best fit curves were generated by regression analysis for these pollutants. In general, pollutant loadings increase at a diminishing rate for incremental increases in runoff volumes. This confirms that the availability of source pollutants is reduced as runoff volume increases. Therefore, the average pollutant concentrations in the larger events are lower due to dilution. The larger runoff events however, contribute larger event pollutant loads.

The correlation coefficients of the fitted curves ranged between 0.81 for suspended solids up to 0.93 for total phosphorus. In Figure 6, a distinct change in slope especially for BOD_5 and TN, was noted for events smaller than 1 mm of runoff. This was attributed to an insufficient rainfall intensity and duration to wash significant amounts of available pollutants. The graphs in Figure 6 can be used to estimate the typical pollutant loads of

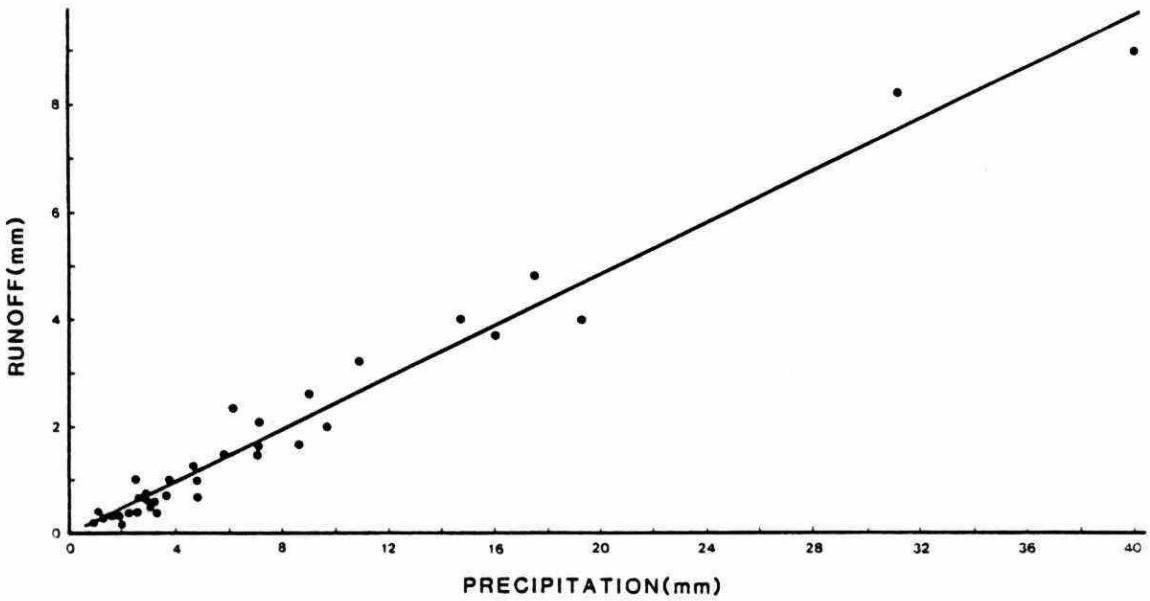

Figure 4. Precipitation - runoff relationship, Devon catchment.

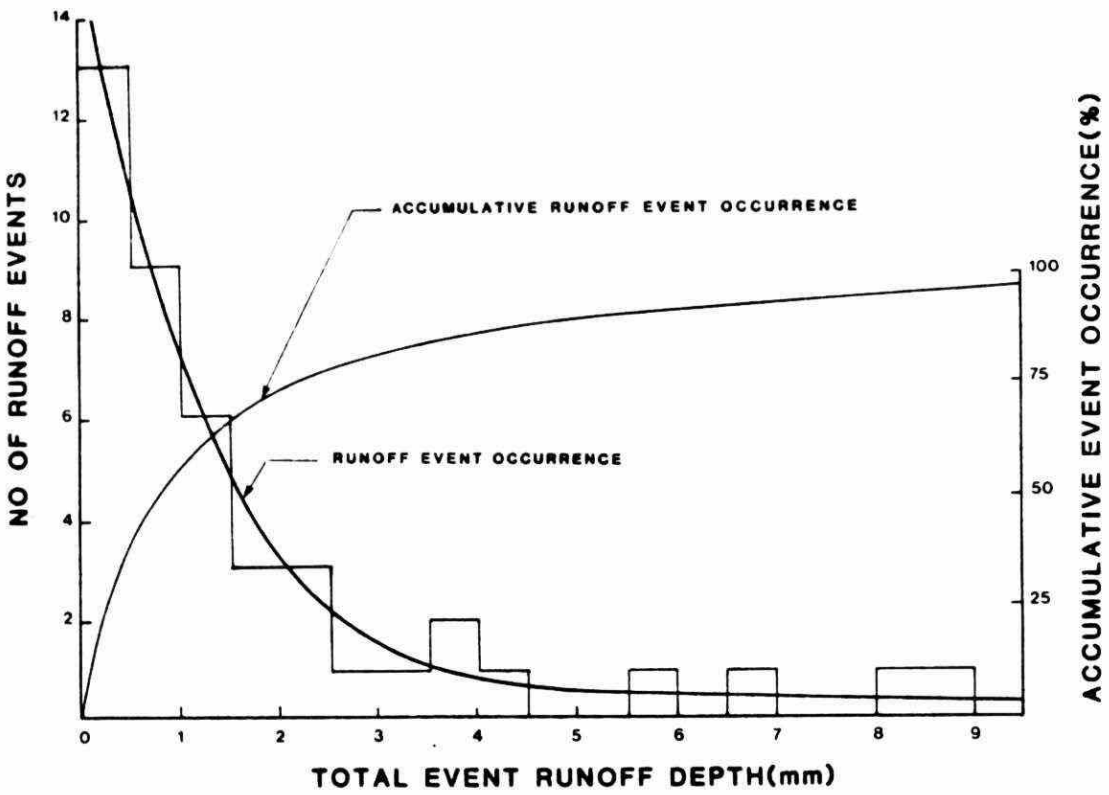

Figure 5. Frequency of seasonal storm events.

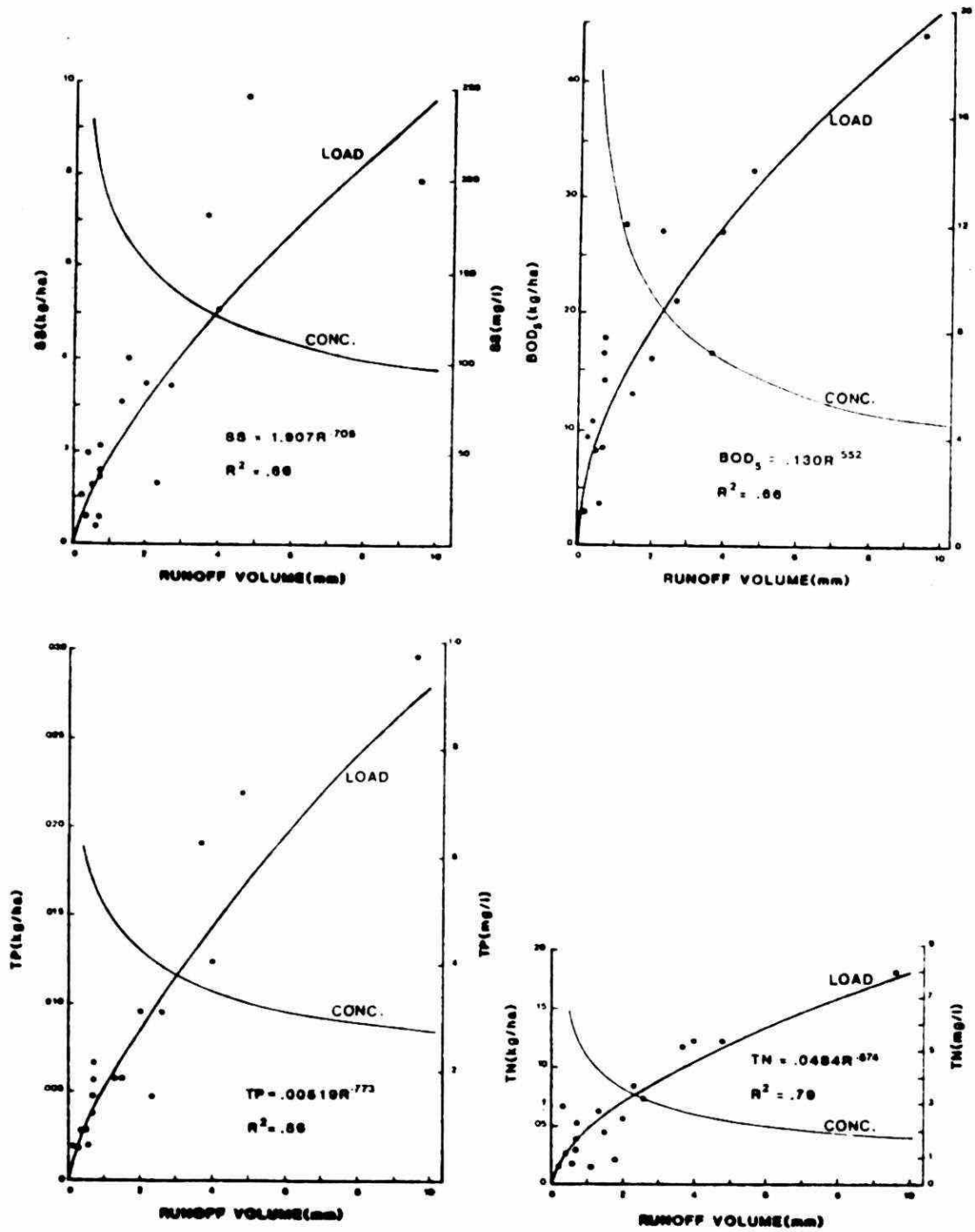

Figure 6. Event pollutant load, concentration and runoff volume relationships, Devon catchment - 1981 season.

given runoff event discharged from the pilot catchment. For example, a runoff of 4 mm results in approximate pollutant loads of 5.3 kg/ha SS, 0.28 kg/ha BOD_5, 0.10 kg/ha TN and 0.014 kg/ha TP.

The observed relationship between event runoff and corresponding typical event loadings presented above was then evaluated on a seasonal basis. This analysis involved taking the product of typical event loadings in Figure 6 and the frequency of these events in Figure 5. The resultant relationships are shown in Figure 7. It is evident that the pollutant loadings were distributed unevenly. The peak seasonal loads were found to be generated by about 1.25 mm runoff events. A major portion of the total seasonal pollutant load results from typical events of up to 4 mm. For example, 4 mm runoff events are expected to generate a total seasonal load of 5.3 kilograms per hectare SS. Events greater than 4 mm runoff appear to be of minor significance in contributing to the total seasonal load.

The magnitude and distribution of the seasonal pollutant loads contributed by runoff events are expected to vary from year to year. These deviations were not investigated. For the purpose of this study however, it can be concluded that frequent runoff events, relatively small in magnitude when compared to typical sewer design storms, contribute the major seasonal pollutant loadings.

MODEL FORMULATION

The data evaluation and interpretation presented a characterization of numerous stormwater runoff events as a function of precipitation and pilot catchment land use. However, a continuous seasonal estimate of storm event loadings from the whole City of Stratford was also required. To reach this goal, a modelling approach was adopted to extrapolate the pilot catchment rainfall, runoff and runoff quality relationships. The Storage, Treatment, Overflow, Runoff Model (STORM) was found useful to fulfill this goal as well as to allow for the evaluation of control options. Model descriptions and theory are described in the STORM User's Manual (1977).

As a prerequisite to model application to the entire city, STORM was calibrated and verified on the basis of the pilot catchment. This process was necessary to ensure that predicted and recorded events were in good agreement. The results of model calibration and verification, with respect to both runoff quantity and quality, are presented in the following sections.

Runoff

STORM runoff calibration for Devon was conducted with respect to total event runoff volumes. Four events were selected from the catchment encompassing the full range of collected storm events as shown in Table 4. The corresponding precipitation ranged from about 3 mm to approximately 31 mm, thus allowing for a meaningful assessment of urban runoff response and model performance

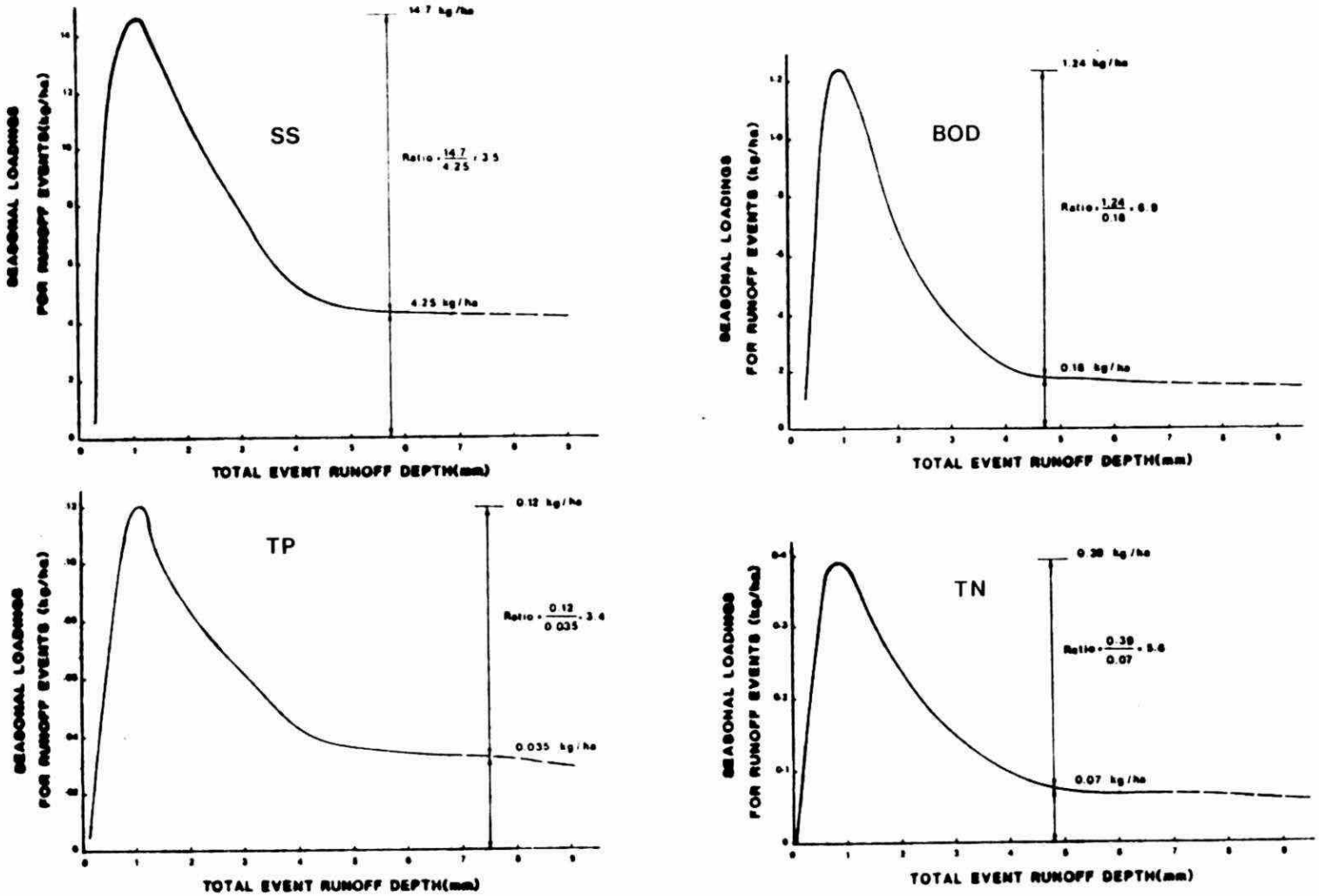

Figure 7. Seasonal pollutant loadings for stormwater runoff events, Devon catchment - 1981 season.

Table 4. Results of storm runoff volume calibration and verification, Devon catchment.

Date of Rainfall Occurrence	Rainfall mm	Simulated Runoff Volume mm	Predicted Runoff Volume mm
Calibration			
28/04/81	16.0	3.7	3.7
25/05/81	2.8	0.6	0.6
16/06/81	7.1	1.5	1.6
22/06/81	31.2	8.2	8.4
Mean	14.3	3.5	3.6
Verification			
22/09/80	32.5	10.0	8.7
01/10/80	22.4	5.0	5.7
11/04/81	8.6	1.7	1.8
13/04/81	24.1	5.2	5.8
22/04/81	10.2	2.3	2.2
10/05/81	4.6	1.4	1.1
10/05/81	14.7	4.0	3.6
11/05/81	4.8	1.0	1.1
27/05/81	2.8	0.7	0.5
13/06/81	9.1	2.6	2.0
21/06/81	17.5	4.8	4.2
04/07/81	2.5	0.6	0.4
17/07/81	4.8	0.7	0.9
26/07/81	7.1	1.6	1.5
04/08/81	13.2	2.6	2.9
Mean	11.9	2.9	2.8

verification.

The simulation results compare well with measured runoff volumes. Approximately 89% of the simulated runoff events were also within a 25% error margin. Small deviations between observed and simulated runoffs can be explained by the simplistic precipitation - runoff relationship that exists for well defined urban catchments with significant impervious areas. This relationship is typically linear with few exceptions because most of the runoff is contributed by impervious areas. Therefore runoff from most urban storm sewered areas can be predicted well using relatively simple models such as STORM. Deviations between observed and predicted results are mainly attributed to measurement accuracy and assumptions made for representative precipitation and wet weather baseflow corrections.

Deviations exist for individual events or over the average of a few events as shown in the calibration sections of Table 4. However, for a large number of events the deviation between the average observed runoff and average predicted runoff is considerably reduced. This is shown in the verification sections of Table 4 where the difference between the overall average observed and predicted runoff is negligible. The overall model ability to consistently predict runoff events is shown in Figure 8.

Runoff Quality

STORM in conjunction with the pollutant-runoff relationships was used to predict urban runoff quality in terms of event pollutant loads. The model was developed and tested based on Devon and other pilot catchment data.

The results showing model ability to predict event pollutant loadings are presented in Table 5. The comparison between measured and predicted values were found agreeable considering the simplistic modelling approach. The accuracy of the predicted results were acceptable for the purpose of this study. Most of the predicted pollutant loads were within 50 percent of the measured loads.

STORMWATER QUALITY CONTROL BY STORAGE

Measures for the abatement of pollution due to stormwater runoff include source controls, collection system controls, and end of pipe controls. Only storage as an end of pipe control is discussed here.

Quality control ponds, in general, are small storage facilities situated at the outlet of the storm sewer system to allow for capture and removal of sediment and assocated pollutants by settling or other means.

From Figure 9, it is evident that small and more frequent storm events wash the most significant portion of the total seasonal loadings to the receiving stream. As shown, this applies for events of up to 4 mm of the total runoff which is equivalent to about 16 mm

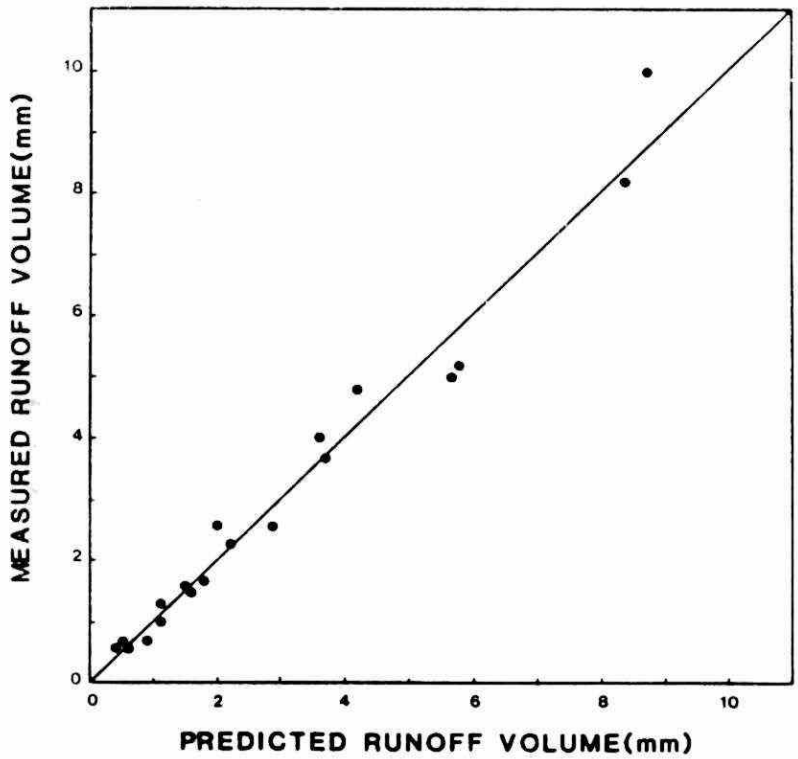

Figure 8. Measured versus predicted event runoff volumes, Devon catchment.

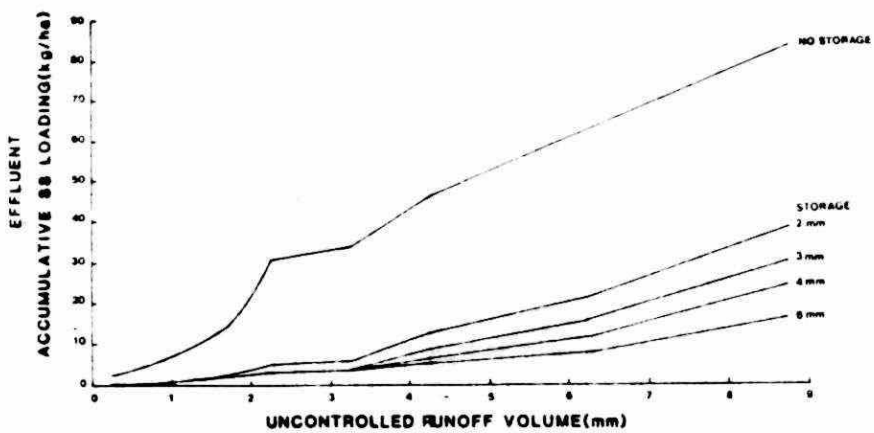

Figure 9. Storage versus suspended solids load reductions.

Table 5. Model performance with respect to event pollutant loads, Devon catchment.

STORM DATE	TOTAL EVENT LOADINGS (kg)							
	Suspended Solids		Biochemical* Oxygen Demand		Total Nitrogen		Total Phosphorus	
	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted
Calibration								
28/04/81	245	232	5.7	9.1	4.0	3.5	0.065	0.46
13/06/81	118	136	7.2	6.5	2.5	2.5	0.33	0.30
16/06/81	138	110	4.5	5.5	1.5	2.1	0.20	0.24
21/06/81	330	371	11.1	9.8	4.2	3.8	0.75	0.51
Verification								
22/04/81	47	96	9.3	6.9	2.9	2.6	0.16	0.32
23/04/81	67	24	3.7	3.0	0.9	1.1	0.10	0.11
23/04/81	21	39	34.2	4.4	2.3	1.7	0.07	0.18
10/05/81	106	44	9.5	4.7	2.1	1.7	0.20	0.19
10/05/81	174	166	9.3	9.0	4.2	3.4	0.42	0.45
27/05/81	55	25	4.9	3.0	1.8	1.1	0.23	0.11
08/06/81	73	16	7.2	2.3	1.0	0.8	0.16	0.07
01/07/81	21	16	5.7	2.3	1.3	0.8	0.20	0.07
04/07/81	37	6	1.0	1.2	0.5	0.4	0.07	0.03
04/07/81	119	122	5.5	5.9	1.9	2.2	0.33	0.26
04/07/81	13	18	1.2	2.7	0.6	1.0	0.17	0.09
17/07/81	51	49	6.1	3.6	1.8	1.6	0.13	0.76
18/07/81	44	42	2.8	3.9	1.1	1.5	0.10	0.15
28/07/81	270	1198	15.1	18.0	6.2	7.1	1.01	1.14

* 5-Day Biochemical Oxygen Demand

of the total precipitation in this case.

The type of storage suggested for the pollutant abatement is off-line (off-stream), located at or near sewer outfalls to the receiving stream. Such facilities, designed according to the size and land use of the drainage area, would capture the most frequent events. In the case of large or closely spaced events exceeding the given storage volume, it is expected that the first flush would be captured and undisturbed by the by-passed portion of the event. Therefore the largest events which contribute the largest single event pollutant loads would also be controlled efficiently. The pollutant concentrations would be lower in the remainder of the event which is by-passed.

The use of off-line storage facilities was investigated for the Devon catchment to demonstrate the potential for the control of stormwater runoff quality. The efficiency of tanks capable of storing 2, 3, 4, and 6 mm runoff events was tested using STORM generated runoff volumes and suspended solids loads for the period of May to September in 1980. The output from STORM served as input to each of the storage facilities. Portions of single events or series of closely spaced events exceeding the volume of the tank were by-passed.

The accumulative seasonal suspended solids loadings are shown in Figure 9. Note that the plotted curve does not increase significantly for the small runoff events up to 4 mm as expected. This is attributed to the fact that the STORM model considers a series of closely spaced events as one event.

The stormwater treatment assumptions were based on the work by Kronis, 1982. Kronis indicated that natural settling of stormwater for 10 hours could typically remove an average of 88% suspended solids, 36% BOD_5, and 47% total phosphorus. Based on these findings, the suspended solids reductions for Devon were plotted in Figure 9. Figure 9 indicates that a 2 mm off-line storage facility has the potential for reducing the seasonal SS loading by as much as 54%. Higher reductions of 64%, 71% and 81% were obtained for 3, 4, and 6 mm storage volumes respectively.

Given the above maximum attainable SS reduction of 88% for the assumed storage conditions, the 6 mm storage volume appears to be an upper limit to the practical storage volume. The most effective storage volume appears to be in the 2 mm range. These findings may be useful in establishing guidelines on how to size storage facilities to meet receiving stream quality objectives.

CONCLUSIONS

On the basis of the assessment of urban stormwater runoff and runoff quality from the pilot catchment the following conclusions are made:

1) The average conventional parameter concentrations were found to be 190 mg/l SS, 13.7 mg/l BOD_5, 4.7 mg/l TN and 0.48 mg/l TP. These values are comparable to the adopted values for Ontario stormwater runoff composition.

2) The event pollutant loading increases with increasing event runoff volume.

3) Smaller runoff events occur more frequently and have higher average pollutant concentrations. As a result, these events contribute the major portion of the total seasonal pollutant loadings.

4) High concentrations of pollutants occur in the first flush of runoff events.

5) The urban stormwater runoff loadings discharged to the receiving stream on a seasonal basis can be reduced by water quality storage ponds. The 1980 Devon catchment SS loading for example, could potentially be reduced by 54% using a storage facility which retains 2 millimeters of runoff over the drainage area. A 6 mm storage facility could result in up to an 81% reduction in SS. A 2 mm and 6 mm runoff event refers to a precipitation of about 8 mm and 24 mm rainfall respectively.

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